Kinematic viscosity of biodiesel fuel components and related compounds. Influence of compound structure and comparison to petrodiesel fuel components

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Abstract

Biodiesel, defined as the mono-alkyl esters of vegetable oils and animal fats is an alternative diesel fuel that is steadily gaining attention and significance. One of the most important fuel properties of biodiesel and conventional diesel fuel derived from petroleum is viscosity, which is also an important property of lubricants. Ranges of acceptable kinematic viscosity are specified in various biodiesel and petrodiesel standards. In this work, the kinematic viscosity of numerous fatty compounds as well as components of petrodiesel were determined at 40 °C (ASTM D445) as this is the temperature prescribed in biodiesel and petrodiesel standards. The objective is to obtain a database on kinematic viscosity under identical conditions that can be used to define the influence of compound structure on kinematic viscosity. Kinematic viscosity increases with chain length of either the fatty acid or alcohol moiety in a fatty ester or in an aliphatic hydrocarbon. The increase in kinematic viscosity over a certain number of carbons is smaller in aliphatic hydrocarbons than in fatty compounds. The kinematic viscosity of unsaturated fatty compounds strongly depends on the nature and number of double bonds with double bond position affecting viscosity less. Terminal double bonds in aliphatic hydrocarbons have a comparatively small viscosity-reducing effect. Branching in the alcohol moiety does not significantly affect viscosity compared to straight-chain analogues. Free fatty acids or compounds with hydroxy groups possess significantly higher viscosity. The viscosity range of fatty compounds is greater than that of various hydrocarbons comprising petrodiesel. The effect of dibenzothiophene, a sulfur-containing compound found in petrodiesel fuel, on viscosity of toluene is less than that of fatty esters or long-chain aliphatic hydrocarbons. To further assess the influence of the nature of oxygenated moieties on kinematic viscosity, compounds with 10 carbons and varying oxygenated moieties were investigated. A reversal in the effect on viscosity of the carboxylic acid moiety vs. the alcohol moiety is noted for the C10 compounds compared to unsaturated C18 compounds. Overall, the sequence of influence on kinematic viscosity of oxygenated moieties is $COOH \approx C\text{–}OH > COOCH_3 \approx C{=}O > C\text{–}O\text{–}C >$ no oxygen.
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1. Introduction

Biodiesel is an alternative diesel fuel obtained by transesterifying vegetable oils or other materials largely comprised of triacylglycerols, such as animal fats or used frying oils, with monohydric alcohols to give the corresponding mono-alkyl esters [1,2]. Production and use of biodiesel has increased significantly in many countries around the world and it is in nascent status in numerous others. While biodiesel faces some technical challenges such as reducing of NO_x exhaust emissions, improving oxidative stability and cold flow properties, advantages of biodiesel compared to petrodiesel include reduction of most exhaust emissions, improved biodegradability, higher flash point and domestic origin. Biodiesel is also largely compatible with the existing fuel distribution infrastructure.

Reducing viscosity is the major reason why vegetable oils or fats are transesterified to biodiesel because the high

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Table 1
Kinematic viscosity in diesel fuel standards

Standard	Location	Fuel	Method[a]	Kinematic viscosity (mm^2/s)
ASTM D975	United States	Petrodiesel	ASTM D445	1.9–4.1[b]
ASTM D6751	United States	Biodiesel	ASTM D445	1.9–6.0
EN 590	Europe	Petrodiesel	ISO 3104	2.0–4.5
EN 14214	Europe	Biodiesel	ISO 3104	3.5–5.0

[a] ASTM, American Society for Testing and Materials; ISO, International Standards Organization.
[b] Specification for low-sulfur No. 2 diesel fuel to which biodiesel is usually compared. Specification for No. 1 diesel fuel is 1.3–2.4 mm^2/s.

viscosity of neat vegetable oils or fats ultimately leads to operational problems such as engine deposits. It is also a property any 'designer' fuel modified for fatty acid composition or alcohol used for transesterification would need to meet. Table 1 lists the kinematic viscosity specifications contained in standards for biodiesel and conventional, petroleum-derived diesel fuel (petrodiesel) in the United States and Europe [3–6]. The viscosity of biodiesel is slightly greater than that of petrodiesel but approximately an order of magnitude less than that of the parent vegetable oil or fat [1,2]; see also data in this paper. Biodiesel and its blends with petrodiesel display temperature-dependent viscosity behavior similar to that of neat petrodiesel [7]. An application of the viscosity difference of biodiesel and its parent oil or fat is monitoring of the transesterification reaction [8].

Viscosity data of pure fatty esters can be used for predicting the viscosity of the mixture of fatty esters comprising biodiesel [9]. Dynamic [9–14] and kinematic [15–17] viscosity data (which are related by density as a factor) of some individual fatty compounds are available in the literature and some data have been compiled [1,2,18]. Kinematic viscosity (at 40 °C), however, is the parameter required by biodiesel and petrodiesel standards. However, the data in the literature vary not only by dynamic vs. kinematic viscosity but also by temperature with most data not obtained at 40 °C with some data being redundant. On the other hand, data on the influence of some structural features on viscosity of fatty compounds are available only with difficulty or not at all, although some of these aspects were discussed in a general fashion in more dated literature [19,20]. This paper, therefore, reports the kinematic viscosity of a range of fatty compounds determined under identical conditions at 40 °C covering structural features such as chain length, varying the acid and alcohol moieties of esters as well as number, nature and configuration of double bonds. Some free fatty acids and fatty alcohols are also included. These data are discussed with respect to biodiesel fuel standards. The data are also compared to some compounds occurring prominently in petrodiesel fuels. Some literature references for kinematic viscosity data of

some branched and straight-chain aliphatic as well as aromatic hydrocarbons as they can occur in petrodiesel are [21–23].

2. Experimental

All straight-chain esters (methyl, ethyl, *n*-propyl, *n*-butyl) were purchased from NuChek-Prep, Inc. (Elysian, MN) and were of purity >99% as confirmed by random checks (nuclear magnetic resonance spectroscopy (NMR), Bruker (Billerica, MA) Avance 500 spectrometer operating at 500 MHz for ^{1}H NMR with $CDCl_3$ as solvent, and/or gas chromatography-mass spectrometry (GC-MS), Agilent Technologies (Palo Alto, CA) 6890 gas chromatograph coupled to an Agilent Technologies 5973 mass selective detector at 70 eV, HP-5 capillary column) of some materials. Branched esters were either synthesized by *p*-toluenesulfonic acid-catalyzed esterification of the corresponding acid with the alcohol and purified by high-performance liquid chromatography (HPLC) (for a procedure see Ref. [24]) of the corresponding fatty acid or were purchased from ChemService (West Chester, PA) or TCI America (Portland, OR) and purified [24] and selected for analysis [25] as described. Straight-chain and branched alkanes, aromatic (including dibenzothiophene and its O, N and C homologues) and alkylated aromatic compounds, all in purities ≥98% (in most cases ≥99%; verified by GC-MS analyses) were purchased from Aldrich (Milwaukee, WI) and used as received after purity was checked by GC-MS as mentioned above. Biodiesel (methyl soyate) was obtained from Ag Environmental Products, Lenexa, KS. Petrodiesel fuels were obtained from the Department of Agricultural Engineering, University of Illinois, Urbana, IL (No. 2 diesel fuel), Midwest Oil Co., Peoria, IL (No. 1 diesel fuel), and from the Air National Guard, Peoria, IL (jet fuel JP-8).

Kinematic viscosity values were determined with Cannon-Fenske viscometers (Cannon Instrument Co., State College, PA) at 40 °C following the standard method ASTM D445 [26]. All viscosity data reported here are means of triplicate determinations. Reproducibility of the viscosity data was excellent, with all $R^2 > 0.99$.

3. Results and discussion

The kinematic viscosity of fatty compounds is given in Tables 2–4. Table 2 lists the kinematic viscosity values of common saturated fatty esters, the most common unsaturated fatty esters such as those of oleic, linoleic and linoleic acids as well as of some corresponding triacylglycerols (triglycerides) and fatty alcohols. Table 3 compares the kinematic viscosity of several monounsaturated fatty acid methyl esters, among them *cis* and *trans* isomers of methyl octadecenoate with the unsaturation in three different positions in the chain. Table 4 presents the kinematic

Table 2
Kinematic viscosity (40 °C; mm²/s) of saturated and unsaturated fatty compounds

Acid/alcohol/ester	Fatty acid structure								
	C10:0	C12:0	C14:0	C16:0	C18:0	C18:1	C18:2	C18:3	C18:1-12-OH
TAG[a]	nd[b]	nd	nd	nd	nd	32.94	24.91	17.29	nd
Acid	5.63	nd	nd	nd	nd	19.91	13.46	nd	nd
Alcohol	8.24	nd	nd	nd	nd	17.53	11.94	nd	142.21
Methyl	1.72	2.43	3.30	4.38	5.85	4.51	3.65	3.14	15.44
Ethyl	1.87	2.63	3.52	4.57	5.92	4.78	4.25	3.42	nd
Propyl	2.30	3.04	4.05	5.30	6.78	5.44	4.39	nd	nd
iso-Propyl	nd	nd	3.91	5.20	nd	nd	nd	nd	nd
Butyl	2.60	3.39	4.47	6.49	7.59	5.69	4.80	nd	nd
iso-Butyl	nd	3.48	4.65	6.02	nd	nd	nd	nd	nd

Systematic (trivial) names of fatty acids in this table in the sequence of the columns from left to right: Decanoic (caprylic) acid, dodecanoic (lauric) acid, tetradecanoic (myristic) acid, hexadecanoic (palmitic) acid, octadecanoic (stearic) acid, 9(Z)-octadecenoic (oleic) acid, 9(Z),12(Z)-octadecadienoic acid (linoleic acid), 9(Z),12(Z),15(Z)-octadecatrienoic (linolenic) acid, 12-hydroxy-9(Z)-octadecenoic (ricinoleic) acid. Systematic (trivial names) of the fatty alcohols: 9(Z)-octadecen-1-ol (oleyl alcohol); 9(Z),12(Z)-octadecadien-1-ol (linoleyl alcohol), 9(Z)-octadecene-1,12-diol (ricinoleyl alcohol).

[a] Triacylglycerol (triglyceride).
[b] Not determined. Most of these materials are solids at 40 °C.

viscosities of compounds with 10 carbons in the chain containing different oxygenated moieties in order to compare the effect of the latter without changing the number of carbon atoms. Table 5 gives the kinematic viscosity of petrodiesel and prominent hydrocarbon components thereof as well as some related compounds. The existence of most of these compounds in petrodiesel was checked by GC-MS analysis of three petrodiesel fuels as mentioned above. Table 6 lists kinematic viscosities of solutions of methyl oleate, dibenzothiophene and hexadecane in toluene. The results presented here coincide well with some kinematic viscosity data given elsewhere for fatty acid methyl esters [16] as well as fatty acids and

triacylglycerols [15] or dynamic viscosity of fatty acids [10] and esters [9]. Also, fatty esters are Newtonian fluids at temperatures above 5 °C [27]. For sake of comparison, the kinematic viscosity values of a sample of commercial biodiesel (methyl soyate) was 4.09 mm²/s and the values for petrodiesel fuels were 1.54 mm²/s for No. 1 diesel fuel, 2.70 mm²/s for No. 2 diesel fuel and 1.39 mm²/s for jet fuel JP-8.

For all fatty compounds and aliphatic hydrocarbons, kinematic viscosity increases with chain length (number of carbons; see Tables 2, 3 and 5). Generally, the aliphatic and aromatic hydrocarbons, which are the major components of petrodiesel, display a smaller viscosity range (Table 5) with lower viscosities due to their lack of oxygen or other heteroatoms. When extending the chain by the same number of carbons, differences in viscosity increase are smaller for hydrocarbons than for fatty acid alkyl esters. For example, the kinematic viscosity of fatty acid methyl esters increases by 2.66 mm²/s from methyl decanoate to methyl palmitate and 1.96 mm²/s from decane to hexadecane.

For the same number of carbon atoms, fatty compounds have greater kinematic viscosity than their hydrocarbon counterparts. For example, pentadecane has a lower kinematic viscosity than propyl laurate and methyl

Table 3
Kinematic viscosity (40 °C; mm²/s) of some unsaturated acid fatty methyl esters including isomers of methyl octadecenoate

Chain length and double bond position	Double bond configuration	
	cis	trans
14:1; Δ9	2.73	nd
16:1; Δ9	3.67	nd
18:1; Δ6	4.64	5.51
18:1; Δ9	4.51[a]	5.86
18:1; Δ11	4.29	5.41
18:1, Δ9, 12–OH	15.44	nd
18:2, Δ9,12	3.65[a,b]	5.33[b]
20:1, Δ11	5.77	nd
22:1, Δ13	7.33	nd

Systematic (trivial names) of compounds in this table: methyl 9(Z)-tetradecenoate (methyl myristoleate), methyl 9(Z)-hexadecenoate (methyl palmitoleate), methyl 6(Z)-octadecenoate (methyl petroselinate), methyl 6(E)-octadecenoate (methyl petroselaidate), methyl 9(Z)-octadecenoate (methyl oleate), methyl 9(E)-octadecenoate (methyl elaidate), methyl 11(Z)-octadecenoate (methyl cis-vaccenate), methyl 11(E)-octadecenoate (methyl vaccenate), methyl 12-hydroxy-9(Z)-octadecenoate (methyl ricinoleate), methyl 9(E),12(E)-octadecadienoate (methyl linolelaidate), methyl 11(Z)-eicosenoate, methyl 13(Z)-docosenoate (methyl erucate).
[a] Value also given in Table 2.
[b] Values for all-cis or all-trans configuration.

Table 4
Kinematic viscosity (40 °C; mm²/s) of some oxygenated compounds with 10 carbon atoms

Compound	Kinematic viscosity
Decane[a]	0.97
Dipentyl ether	1.08
2-Decanone	1.47
Decanoic acid[b]	5.63
Methyl nonanoate	1.44
1-Decanol[c]	8.04

[a] See also Table 5.
[b] See also Table 2.
[c] See also Table 2.

Table 5
Kinematic viscosity (40 °C; mm^2/s) of prominent components of petrodiesel and some related compounds

Compound	Kinematic viscosity	Compound	Kinematic viscosity
Aliphatic compounds			
Saturated alicyclic compounds		Cyclic compounds	
Hexane	0.42	Cyclohexane	0.93
		Ethyl cyclohexane	0.86
		Propyl cyclohexane	0.99
		Butyl cyclohexane	1.22
		cis-Decahydronaphthalene (Decalin)	2.52
		trans-Decahydronapthalene (Decalin)	1.745
		Unsaturated compounds	
Decane	0.97		
Undecane	1.20		
Dodecane	1.46	1-Dodecene	1.30
Tetradecane	2.09	1-Tetradecene	1.98
Pentadecane	2.49		
Hexadecane	2.93	1-Hexadecene	2.70
2,2,4,4,6,8,8-Heptamethylnonane	3.14		
		1-Octadecene	3.58
Aromatic compounds (with substituents)			
Benzene	0.58	1-Methylnaphthalene	2.41
Toluene	0.57	2-Methylnaphthalene	1.52
Ethylbenzene	0.63	1,2-Dimethylnaphthalene	2.83
Propylbenzene	0.78	1,3-Dimethylnaphthalene	2.33
1,2,3,4-Tetrahydronaphthalene (Tetralin)	1.60		

myristate, which have the same number of carbons. However, if oxygen atoms are considered on an equal basis with carbon atoms, the kinematic viscosity of fatty esters is approximately equal to that of the corresponding aliphatic hydrocarbons for the chain lengths studied here. Some examples are the comparison of the kinematic viscosities of methyl laurate (13 C+2 O) vs. pentadecane (15 C), ethyl laurate (14 C +2 O) vs. hexadecane and ethyl decanoate (12 C+2 O) vs. tetradecane.

Double bonds reduce kinematic viscosity in both fatty compounds and aliphatic hydrocarbons. However, these results for double bonds should not be compared quantitatively as the positions of the double bonds were towards the middle of the chain in the fatty compounds and at C-1 for the hydrocarbons. The viscosity-lowering effect was greater in the fatty compounds, which may be a result of the double

bond position. However, varying the double bond position (Table 3) towards the middle of the chain has comparatively little effect on viscosity (Table 3) of methyl octadecenoate, so that double bond isomerization within this region should not be of significance for biodiesel.

The data in Table 3 also show that *trans* double bonds impart higher viscosity than *cis* double bonds, an effect already noted some time ago [19,20]. The viscosity of the *trans* compounds is approximately that of the corresponding saturated compound. This effect is greater than varying the double bond position. This is of significance for the use of 'waste' oils (such as frying oils) as biodiesel, as they usually are partially hydrogenated and frequently contain higher amounts of *trans* fatty acid chains. For all neat *trans* isomers of methyl octadecenoate, the kinematic viscosity exceeded the upper limit of 5 mm^2/s prescribed in the European

Table 6
Kinematic viscosities (40 EC; mm^2/s), of hexadecane, dibenzothiophene, methyl oleate and methyl palmitate in toluene

% Toluene	% Addition	Addition			
		Hexadecane	Dibenzothiophene[a]	Methyl oleate	Methyl palmitate
100	0	0.570	0.570	0.570	0.570
99	1	0.559	0.560	0.563	0.560
98	2	0.565	0.582	0.571	0.568
95	5	0.585	0.595	0.602	0.595
90	10	0.620	0.610	0.653	0.653
80	20	0.702	0.670	0.765	0.765
70	30	0.806	–	0.906	0.885
60	40	0.930	–	1.076	1.063
50	50	1.073	–	1.313	1.287
0	100	2.930	–	4.510	4.380

[a] Limited solubility of dibenzothiophene in toluene precluded preparation of solutions of concentration >20%.

biodiesel standard but was within the upper limit of 6 mm^2/s in the American biodiesel standard (Table 1).

The influence of the number of double bonds was investigated for one example (oleic acid, methyl oleate and oleyl alcohol vs. linoleic acid, methyl linoleate and linoleyl alcohol, Tables 2 and 3). The decrease in viscosity caused by the second double bond in the C18:2 compounds was not additive compared to the introduction of one double bond, i.e., an additional double bond does not decrease the viscosity to the extent the introduction of the first double does (methyl oleate vs. methyl stearate). This effect was reported previously [20]. The decrease in viscosity upon introduction of a second double bond was greater for the acid and the alcohol than for the methyl ester moiety.

The introduction of an OH group significantly increases viscosity as the value for methyl ricinoleate (Table 2) shows. This is of significance for the production of castor oil-based biodiesel [28], a fuel that in its neat form exceeds all kinematic viscosity specifications in biodiesel standards due to the high content of ricinoleic acid in castor oil. The additional oxygen in fatty acids vs. fatty alcohols does not contribute significantly to viscosity as the data for oleic acid vs. oleyl alcohol and linoleic acid vs. linoleyl alcohol show (Table 2). A second OH group causes a significant increase in kinematic viscosity as shown by the comparison of the data for oleyl alcohol and ricinoleyl alcohol (Table 2).

Branching has less effect on kinematic viscosity than presence and nature of double bonds. The viscosity of branched esters (Table 2) did not differ significantly from that of the straight-chain analogs with the same number of carbons. In the case of hydrocarbons, the kinematic viscosity of 2,2,4,4,6,8,8-heptamethylnonane (HMN), the low-quality reference compound on the cetane scale of diesel fuels, was slightly greater than that of hexadecane with the same molecular formula of C$_{16}$H$_{34}$ (Table 5). It has been previously shown that branched esters are competitive with methyl esters and straight-chain analogs in terms of cetane numbers while possessing improved low-tempera-ture flow properties [25]. Thus, with viscosity and cetane numbers being comparable to straight-chain analogs and low-temperature properties being improved, branched fatty esters appear preferable to methyl and straight-chain esters in terms of fuel properties.

A method for assessing the effect of oxygenated moieties on viscosity is to use a series of compounds in which the number of carbon atoms is kept constant while varying the oxygenated moiety. For this purpose, compounds with 10 carbon atoms were selected as they generally are liquids at 40 °C without volatility affecting the experiments. Results are presented in Table 4. For the long-chain unsaturated fatty acids (Table 2) the kinematic viscosity of the free acids was greater than that of the corresponding alcohol while the situation was reversed for the saturated C10 compounds. The kinematic viscosity of the corresponding C2 com-pounds (ethanol 1.07 mm^2/s; acetic acid 0.88 mm^2/s) is in the same order as that of the C10 compounds. This reversal in the effect on viscosity of the fatty acid moiety vs. the alcohol moiety was partially observed previously and may be attributable to differences in intermolecular forces varying with chain length [19]. A detailed investigation of this effect is beyond the scope of the present paper. Therefore, for purposes of this work and in order to accommodate the effect of chain-length dependent reversal of the COOH and OH groups, the following sequence of the effect of oxygenated moieties on viscosity is established: COOH ≈ C–OH > COOCH$_3$ ≈ C=O > C–O–C > no oxygen.

When considering these results, it must be kept in mind that biodiesel is a mixture of several fatty esters with each component contributing to the overall kinematic viscosity. Thus lower-viscosity components can reduce the overall kinematic viscosity to an acceptable range even if some higher-viscosity are present. Methods for calculating or predicting viscosity of mixtures have been presented in the literature see (for example, Ref. [9]) and will not be discussed here.

Besides predicting the viscosity of mixtures, several group contribution methods have been proposed for estimating the viscosity of neat compounds (for an overview, see Ref. [29]). Some deviations were observed when applying these methods to saturated fatty compounds studied here, which coincides with the observation on reliability of these methods in Ref. [29]. These methods also apparently do not account for all structural factors, for example, they do not distinguish double bond configuration. However, different effects of *cis* and *trans* double bonds on viscosity were observed here.

With the advent of low-sulfur petrodiesel, the issue of fuel lubricity has become increasingly important as hydrodesulfurization removes polar compounds responsible for the lubricity of petrodiesel [30,31]. It has been stated that sulfur compounds are not among the compounds imparting to lubricity to diesel fuel in contrast to nitrogen- and oxygen-containing compounds [30,31]. Biodiesel added at low blend levels (1–2%) has been stated to restore lubricity to low-sulfur petrodiesel [32–34].

Since viscosity is an important, but not sufficing, property for imparting lubricity, dibenzothiophene, a sulfur compound in non-desulfurized petrodiesel [35], was investigated for its effect on viscosity. For this purpose, solutions in toluene were prepared due to the high melting point of dibenzothiophene (100 °C) and compared to toluene solutions of hexadecane, methyl oleate and methyl palmitate. The kinematic viscosity of these solutions in toluene is reported in Table 6. However, the limited solubility of dibenzothiophene in toluene and other solvents of low viscosity limited the preparation of its solutions to concentrations ≤20%. Similar observations were made for fluorene, carbazole and dibenzofuran, which are analogues of dibenzothiophene except that the sulfur atom is substituted by carbon, nitrogen and oxygen, respectively.

They were not investigated due to their insolubility in toluene and other low-viscosity solvents in reasonable amounts. The data in Table 6 show that dibenzothiophene imparted a lower kinematic viscosity in toluene solution up to 20% concentration relative to not only methyl oleate and methyl palmitate but also in comparison to the pure hydrocarbon hexadecane. In connection with the above discussion, this result also corroborates observations that the sulfur-containing compounds in non-low-sulfur petrodiesel fuel are not the species responsible for the lubricity of this fuel.

4. Summary and conclusions

The kinematic viscosity of fatty compounds is significantly influenced by compound structure as the present data obtained at 40 °C, the temperature prescribed in biodiesel and petrodiesel standards, show. Influencing factors are chain length, position, number, and nature of double bonds, as well as nature of oxygenated moieties. Generally, the hydrocarbons in petrodiesel exhibit lower viscosity in a narrower range than the fatty esters comprising biodiesel and related fatty compounds with dibenzothiophene affecting viscosity of a low-viscosity solvent less than a long-chain hydrocarbon and fatty esters. In some cases, the viscosity of the fatty acids comprising a certain feedstock may affect the utility of the resulting esters as biodiesel fuel. Branched esters, which have improved low-temperature properties, are competitive with other esters in terms of kinematic viscosity and previously determined cetane number.

5. Disclaimer

Product names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA implies no approval of the product to the exclusion of others that may also be suitable.

References

[1] Knothe G, Dunn RO. Biofuels derived from vegetable oils and fats. In: Gunstone FD, Hamilton RJ, editors. Oleochemical manufacture and applications. Sheffield, UK: Sheffield Academic Press; 2001. p. 106–63.

[2] Dunn RO, Knothe G. Alternative diesel fuels from vegetable oils and animal fats. J Oleo Sci 2001;50(5):415–26.

[3] ASTM standard D6751. Standard specification for biodiesel fuel (B100) blend stock for distillate fuels. ASTM, West Conshohocken, PA.

[4] ASTM standard D975. Standard specification for diesel fuel oils. ASTM, West Conshohocken, PA.

[5] EN14214. Automotive fuels–fatty acid methyl esters (FAME) for diesel engines—requirements and test methods. Berlin, Germany: Beuth-Verlag.

[6] EN590. Automotive fuels-diesel-requirements and test methods. Berlin, Germany: Beuth-Verlag.

[7] Tat ME, Van Gerpen JH. The kinematic viscosity of biodiesel and its blends with diesel fuel. J Am Oil Chem Soc 1999;76(12):1511–3.

[8] De Filippis P, Giavarini C, Scarsella M, Sorrentino M. Transesterification processes for vegetable oils: a simple control method of methyl ester content. J Am Oil Chem Soc 1995;71(12):1399–404.

[9] Allen CAW, Watts KC, Ackman RG, Pegg MJ. Predicting the viscosity of biodiesel fuels from their fatty acid ester composition. Fuel 1999;78(11):1319–26.

[10] Noureddini H, Teoh BC, Clements LD. Viscosities of vegetable oils and fatty acids. J Am Oil Chem Soc 1992;69(12):1189–91.

[11] Fernandez-Martin F, Montes F. Viscosity of multicomponent systems of normal fatty acids: principle of congruence. J Am Oil Chem Soc 1976;53(4):130–1.

[12] Shigley JW, Bonhorst CW, Liang CC, Althouse PM, Triebold HO. Physical characterization of a) a series of ethyl esters and b) a series of ethanoate esters. J Am Oil Chem Soc 1955;32(4):213–5.

[13] Gros AT, Feuge RO. Surface and interfacial tensions, viscosities, and other physical properties of some n-aliphatic acids and their methyl and ethyl esters. J Am Oil Chem Soc 1952;29(8):313–7.

[14] Kern DQ, Van Nostrand W. Heat transfer characteristics of fatty acids. Ind Eng Chem 1949;41(10):2209–12.

[15] Valeri D, Meirelles AJA. Viscosities of fatty acids, triglycerides, and their binary mixtures. J Am Oil Chem Soc 1997;74(10):1221–6.

[16] Gouw TH, Vlugter JC, Roelands CJA. Physical properties of fatty acid methyl esters. VI. Viscosity. J Am Oil Chem Soc 1966;43(7):433–4.

[17] Bonhorst CW, Althouse PM, Triebold HO. Esters of naturally occurring fatty acids. Ind Eng Chem 1948;40(12):2379–84.

[18] Formo MW. Physical properties of fats and fatty acids. 4th ed. Bailey's industrial and oil products. vol. 1. New York: Wiley; 1979 p. 177–232.

[19] Teeter HM, Cowan JC. Viscometric properties of higher fatty acids and their derivatives. J Am Oil Chem Soc 1956;33(4):163–9.

[20] Kaufmann HP, Funke S. The field of fats. LIX. The viscometry of fats (Zur Viskometrie der Fette (Studien auf dem Fettgebiet, 59. Mitteilung.)). Fette u Seifen 1938;45(5):255–62.

[21] Trenzado JL, Matos JS, Segade L, Carballo E. Densities, viscosities, and related properties of some (methyl ester + alkane) binary mixtures in the temperature range from 283.15 to 293.15 K. J Chem Eng Data 2001;46(4):974–83.

[22] Lal K, Tripathi N, Dubey GP. Densities, viscosities, and refractive indices of binary liquid mixtures of hexane, decane, hexadecane, and squalane with benzene at 298.15 K. J Chem Eng Data 2000;45(5):961–4.

[23] Geist JM, Cannon MR. Viscosities of pure hydrocarbons. Ind Eng Chem Anal Ed 1946;18(10):611–3.

[24] Knothe G, Dunn RO, Shockley MW, Bagby MO. Synthesis and characterization of some long-chain diesters with branched or bulky moieties. J Am Oil Chem Soc 2000;77(8):865–71.

[25] Knothe G, Matheaus AC, Ryan III TW. Cetane numbers of branched and straight-chain fatty esters determined in an ignition quality tester. Fuel 2003;82(8):971–5.

[26] ASTM standard D445. Standard test method for kinematic viscosity of transparent and opaque liquids. ASTM, West Conshohocken, PA.

[27] Srivastava A, Prasad R. Rheological behavior of fatty acid methyl esters. Indian J Chem Technol 2001;8(6):473–81.

[28] de Oliveira D, Di Luccio M, Faccio C, Dalla Rosa C, Bender JP, Lipke N, et al. Optimization of enzymatic production of biodiesel from castor oil in organic solvent medium. Appl Biochem Biotechnol 2004;115(1–3):771–80.

[29] Poling BE, Prausnitz JM, O'Connell JP. Viscosity. 5th ed. The properties of gases and liquids. New York: McGraw-Hill; 2001 p. 9.1–9.97.

[30] Mitchell K. Diesel fuel lubricity-base fuel effects. SAE Techn. Pap. Ser. 2001-01-1928 (in Special Publication SP-1628: Diesel and Gasoline Performance and Additives; 2001).

[31] Barbour RH, Rickeard DJ, Elliott NG. Understanding diesel lubricity. SAE Technical Paper Series 2000-01-1918 (in Special Publication SP-1551: Diesel and Gasoline Performance and Additives).

[32] Van Gerpen JH, Soylu S, Tat ME. Evaluation of the lubricity of soybean oil-based additives in diesel fuel. Proc. 1999 ASAE/CSAE-SCGR Annual Intern. Meeting, Paper No. 996134.

[33] Anastopoulos G, Lois E, Serdari A, Zanikos F, Stornas S, Kalligeros S. Lubrication properties of low-sulfur diesel fuels in the presence of specific types of fatty acid derivatives. Energy Fuels 2001; 15(1):106–12.

[34] Schumacher LG, Adams BT. Using biodiesel as a lubricity additive for petroleum diesel fuel. ASAE Paper No. 02-6085; 2002.

[35] Song C. Introduction to chemistry of diesel fuels. In: Song C, Hsu CS, Mochida I, editors. Chemistry of diesel fuels. New York, London: Taylor and Francis; 2000. p. 1–60.